

Will gas be gone in the United Kingdom (UK) by 2050? An impact assessment of urban heat decarbonisation and low emission vehicle uptake on future UK energy system scenarios



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ABSTRACT

The UK government has pledged to reduce its greenhouse gas (GHG) emissions by 80%, from 1990 levels, by 2050. Decarbonisation of transport and heat supply to buildings is recognised as a fundamental step in achieving this target. With cities being the largest producers of GHG emissions they provide the biggest opportunity for climate change mitigation.

Two contrasting visions of a 2050 target-compliant scenario are evaluated against each other. One is based on a high penetration of nuclear power and renewables the other based on predominantly gas with carbon capture storage (CCS). An impact assessment is carried out on both scenarios to understand how each scenario might perform over 4 evaluation criteria.

The evaluation criteria provide insight into each scenario regarding; guaranteeing security of supply, scenario cost, sustainability and how feasible it is to deploy the chosen technologies. Whilst both scenarios raise discussion points on the feasibility of deploying certain technologies the more favourable scenario, in terms of the study results, is the nuclear and renewables option. The renewable energy generating technologies included as part of the study – from largest to smallest in terms of capacity – are wind, solar photovoltaic, tidal and river hydro. The outputs of this study provide an important contribution to academic debate on what might be the most effective approach to achieving the 2050 decarbonisation target.

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1. Introduction and background

The United Nations Framework Convention on Climate Change (UNFCCC) is an international agreement established in 1992. The convention's objective was to stabilise greenhouse gas (GHG) emissions across the world in order to respond to the global threat of climate change. The subsequent Kyoto Protocol established legally binding obligations for countries to reduce their emissions. Most recently, in 2016, the Paris Agreement was adopted to govern GHG emission reductions from 2020. These international treaties are designed to catalyse appropriate mitigation action across the world. The United Kingdom (UK) government - as part of its climate change commitment - has targeted an 80% reduction in GHG emissions by 2050, compared with 1990 levels. In forecasting how the UK might meet this target an extensive debate exists around what might be the most optimal approach.

The impact the urban environment has on contributing to the root cause of climate change cannot be understated. Cities consume over two-thirds of the total amount of energy consumed across the world. Over 70% of all GHG emissions originate from cities [1]. According to the United Nations close to 55% of the global population live in urbanised areas. By 2050 it is expected that this number will increase to over 65% [2].

Carbon dioxide (CO₂) is the most prevalent GHG emitted by human activity. CO₂ is the most commonly-used term when describing accounting for harmful GHGs. National and international carbon emissions accounting shows carbon as carbon dioxide equivalent (CO₂e). This includes the conversion of other GHGs, such as methane from landfill, into their equivalent CO₂ emissions based on their relative global warming potential. This form of accounting aligns with national and international measurement of CO₂ emissions [3].

In the UK close to 50% of final energy consumed relates solely to the provision of heat [4] with a significant amount of energy required as well for transport. London, the UK's largest city, in 2013

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had 36% of emissions being generated from homes, 42% from workplaces and 22% from transport shown in Fig. 1.

Total overall emissions for the UK - most recently for 2015 - are shown in Table 1 along with the corresponding emissions reduction target to be met by 2050. The 2050 target is 167 Mt CO₂e of which 126 Mt CO₂e is the statutory target and 41 MtCO₂e is the allocated allowance for international aviation and shipping (IAS).

In the context of how the UK could meet its 2050 GHG emissions target this study asks the question of whether gas will continue to play a role through to 2050. Focusing on the need to decarbonise heat and transport in the urban environment, two future scenarios are compared using differing technologies with 4 criteria used to provide points of analysis. The evaluation criteria is then used to determine which scenario might be more preferable determining what, if any, future role gas might play.

1.1. Literature review

It has been recognised that substantial progress is required in both the heating and transport sectors to meet the 2050 target. The heating sector is viewed as the most difficult sector to decarbonise with emissions requiring a 65% reduction based on 2015 levels. The challenge in meeting the decarbonisation target lies in that over 80% of domestic buildings in the UK would be required to change their heating technology by 2050 [7].

Various studies have been undertaken to model how a GHG emission target compliant UK energy system may look in 2050. A theme identified, across a range of studies, is that to effectively decarbonise two things need to happen in order. Firstly, the electricity system must become close to emission free and secondly sectors, such as heating and transport, will most likely need to become more reliant on electricity to enable decarbonisation, at the appropriate scale, to take place [8]. Whilst decarbonising the supply of energy is important it is also recognised that reducing energy demand by improving energy efficiency measures of buildings is equally fundamental. It is agreed that ground-breaking profound change is necessary for the UK energy system to effectively decarbonise at the required scale and time-frame. The impacts of this will be felt across the entire energy industry [9]. Different visions of the future exist. Some visions include an all-electric future based on low to zero carbon electricity. However, gas with carbon capture storage (CCS) or instead the use of hydrogen gas to provide heat to homes is viewed as an alternative approach to reducing emissions. Visions for future transport systems being carbon compliant involve, for example, a high electrification of current modes of transport as well as utilising alternative fuels for mobility, such as hydrogen and biofuels.

Whilst debate exists on how the future might look, what is clear is that a huge amount of capital investment is required to ensure a future low carbon energy system. In the short term - due to imminent closures of ageing UK electricity generating infrastructure - the government has estimated that an investment in excess of £100 billion is required to replace soon-to-be redundant capacity [10]. The UK Energy Research Centre (UKERC) has concluded that the average time for an energy generation technology to become commercialised is 48 years. With a 2050 compliant energy system likely to be dependent upon some form of technology which is yet to be fully commercialised investment decisions, followed by action, are likely required in the close to immediate term [11]. Whichever solution(s) is/are adopted National Grid (NG) - the owner and operator of the UK's gas and electricity grid - have stated that action needs to be taken within this decade to ensure a realistic prospect of achieving the 2050 target. The imperative for action in the close to immediate-term makes the contents of this study extremely relevant not only to the future but also to now [12].

Since the inception of the UK's 2050 emissions target - as a consequence of the 2008 UK Climate Change Act - a back casting approach has often been adopted towards forming future scenarios. This means a scenario is formed from establishing the desired target and then working backwards to establish how the scenario looks [13]. A key aim of any energy scenario study is to establish a pathway to achieving the desired target whilst assessing the differing constraints on a range of technologies and resources.

1.2. Introduction to scenarios

In providing an answer to the study question, two future scenarios compliant with meeting the 2050 target are compared. The first consists mainly of nuclear power and renewables. The renewable energy generating technologies included as part of the study - from largest to smallest in terms of capacity - are wind, solar photovoltaic, tidal and river hydro.

The second scenario is based on gas - both natural gas and hydrogen - along with carbon capture storage (CCS). Both scenarios considered are focused on a main energy source; nuclear and renewables in the first scenario and natural gas and hydrogen in the second. Either scenario has its own specific issues around security of supply and the commercial viability of the solutions involved which require careful attention [13]. Whilst the UK has much experience in deploying nuclear, renewables and gas uncertainties do exist which include the need to commercially and technically demonstrate the viability around the storage of radioactive waste, CCS and the conversion of the gas grid to a hydrogen grid.

Whilst previous studies do exist for assessing a variety of future

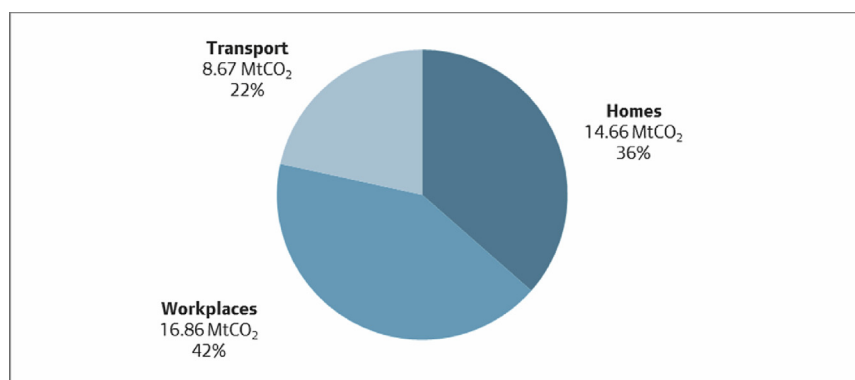


Fig. 1. London's CO₂e Emissions in 2013 by sector [5].

Table 1
2015 UK greenhouse gas emission final figures [6].

	1990 baseline	2015 level	Change from 1990 level	2050 target level	Change from 1990 level
GHG emissions in million tonnes of CO ₂ equivalent (MtCO ₂ e)	800	496.7	38% reduction	c.167	80%

energy scenarios for the UK these studies often fail to consider the energy system as a whole and rather focus on only one component, e.g. just electricity [8]. Instead, this study aims to consider the whole energy system holistically considering the heat, transport and electricity sectors together. Also importantly - in differentiating from other studies - this study considers the specific effect of urban activities, i.e. transport use and heat provision in the context of decarbonisation. The two scenarios are based on the 'Gone Green' scenario from the Future Energy Scenarios (FES) study, published annually by NG [7]. FES shows a range of credible pathways for the future of the UK's energy through to 2050. The scenarios reflect the possible future sources of and demands for electricity and gas.

NG – as a system operator - use the scenarios for planning its operations and network investments with views widely consulted on from many knowledgeable external organisations. The Gone Green scenario provides key data around demand and supply to be used in the model (described in section 2). Gone Green is the only scenario, designed by NG, in which the 2050 GHG emissions reduction target is met.

1.2.1. Background to nuclear and renewables scenario

Advantageously nuclear energy is far more energy dense than most other sources [14]. Nuclear power is also a very reliable provider of base load. As of 2018 there are currently 15 nuclear reactors generating around 20% of UK power but it's expected nearly 50% of these will be retired by the mid-2020s [15]. Since 1987 only one licence has been granted for building a new plant which is Hinkley Point in 2012 [16]. It was initially anticipated for Hinkley point to be operational by 2017 which was then extended to 2025. The expectation is it will be complete by then [17]. Consent for beginning construction was granted in March 2017 and as of early-2018 tunnelling has been undertaken for pipes and cables [18].

However, in contrast to the lack of large-scale nuclear development, NG's Gone Green 2050 scenario puts nuclear at the forefront of generation with the generation capacity more than doubling from what it is now. The largest sources of power in the scenario are close to 40% of all power from wind, 30% from nuclear and 11% from solar.

In this high-electrification scenario nuclear power and renewables are broadly providing the heat and power needs of consumers whilst the national gas grid has become largely redundant and is mostly an unused asset. Transport decarbonisation, under this scenario, is largely in the form of electrification. Due to the reliance of electricity generation from intermittent renewable sources the ability to store electricity is pertinent as is effective smart-grid demand management to help reduce the peak load. However note that demand management falls outside the scope of this study. Other uncertainties exist around energy distribution infrastructure (e.g. grid management and connection), impact on the electricity grid from high electrification and general public acceptance of technologies such as wind (e.g. visual impact) or nuclear (e.g. acceptance of the production of radioactive waste).

1.2.2. Background to gas CCS scenario

A 2013 University College London (UCL) study [19] shows that the gas network currently provides heat to around 23 million properties across the UK. With close to 84% of homes connected to the gas network an assumption is made that the remaining 16% (4.4

million homes) use alternatives such as electrical heating with around 2% of that number connected to a heat network. Gas is commonly viewed as a fuel which can provide a crucial role in transitioning the UK into a lower carbon future. It has been argued that due to its flexibility, low capital cost, and shorter lead in timeframe that gas-fired generation will remain for a long time [20].

Natural gas has useful properties as an energy source. Unlike coal and nuclear it isn't a baseload technology but rather can provide flexibility where required in the energy system to match changing demand [21]. Its lower lag-time compared to other base load technologies means output can be more easily modified.

The premise for a future based on gas is as follows. Gas is an assured, prevalent resource with an existing well-functioning distribution and supply infrastructure. To decarbonise gas it either needs to undertake CCS centrally, prior to being distributed, or else the CCS should take place at the end point of distribution locally to where it's used. In utilising the centralised approach the scenario looks to produce hydrogen from natural gas via steam methane reforming (SMR) at large facilities with CCS and then distribute the hydrogen within the existing gas infrastructure. This is based on the requirement that existing appliances, such as boilers and cookers, all require modification to instead run on hydrogen gas. The CO₂ captured would be mainly stored in the North Sea.

The development of CCS is considered key in decarbonising the UK's electricity system [22] as well as fundamental to meeting the nearer term 2030 decarbonisation target [10] of a 57% reduction based on 1990 levels. The base line data for this scenario is taken from a KPMG 2016 study [9] which in turn was based on NG's Gone Green FES – providing a means of comparing the two scenarios objectively. In its 2016 study KPMG considered the UK gas network's role in a 2050 integrated energy system. Its study produced 4 scenarios with one titled the Evolution of Gas. Under this scenario gas would continue to be the prevalent means of providing heat to buildings however the prevalent source of the gas will be hydrogen along with some natural gas.

Hydrogen fuel cell vehicles provide the majority of road transport with many hydrogen refuelling stations. The railway network is fully electrified with only some electric vehicles existing for short journeys, e.g. taxis. The proportions of gas and electricity - as the heating source for residential and commercial customers under this scenario - are the same as the present day.

1.3. Objectives and structure of study

The outputs of this comparative analytical study will help to contribute to academic debate on what might be the most effective approach to achieving the 2050 GHG emissions reduction target.

The analysis will comprise a comparative exercise of the impacts of pursuing either scenario. The impacts considered will be mainly quantitative of which the results will feed into more qualitative findings. Criteria for analysis will include 2 key areas:

1. Ability of scenario to meet the trilemma of:
 - o energy security – what is the level of reliance on importing energy from other parts of the world?
 - o affordability – what is the full cost of providing energy under the given conditions?

- o sustainability – what is the environmental impact of establishing an energy system based on the given scenarios?
- 2. Feasibility of technology in 2018 - how mature - as well as technically and financially viable - are the proposed technologies for both scenarios?

These points of analysis will provide the means of identifying potential reasons for why one scenario could be more preferable over the other. Additionally, the analysis will support generating the evidence for whether there is a genuine role for gas, or not, by 2050.

Initial data to establish both scenarios is taken from the Gone Green scenario from NG's FES [7]. The data is fed into the EnergyPLAN model [23] to further understand import dependency, environmental impact, ability of the scenario to meet all energy requirements as well as full energy system costings. Relevant literature and data is utilised in understanding technology feasibility. The output of this will provide information and quantified data to answer the study questions provided above. Based on numbers produced through the analysis - in assessing the feasibility of various technologies and using the outputs of the cost model - a marginal abatement cost (MAC) curve diagram will be produced for the more favourable scenario.

2. Scenario definition and model configuration

Due to the many complex and interacting parts of a national energy system it is important to mark out the scope of the study to ensure it is focused on the question being considered. The study is only considering those technologies listed under the 2 scenarios outlined in section 1.2. Measures such as energy efficiency, utilising energy from waste and demand side response all have a clear role in future evolving energy systems but are not included in the study's remit.

EnergyPLAN [23] exists to assist the design of national energy planning strategies on the basis of technical and economic analyses of the consequences of different energy systems and investments. This software has been chosen as it provides a useful means to take different inputs for opposing scenarios but produce results which can be clearly compared and contrasted to provide a meaningful quantified comparison of the scenarios. Data inputs for the model, shown in Fig. 2, include; energy demands, renewable energy sources, energy plant capacities, storage capacity and cost assumptions for capital investment as well as operation and maintenance. Common input data for both scenarios is described below. Input data which differed by scenario was as follows. For the nuclear and renewables scenario:

- heat pumps provide 175 TWh of heat
- input for nuclear generating capacity is 20 GW
- input for renewable energy generating capacity include 51 GW wind, 38 GW of photovoltaic, 8.2 GW of wave and 1.1 GW of river hydro

For the gas CCS scenario:

- hydrogen provides 210 TWh of heat via micro combined heat and power (CHP)
- petrol provides 100 TWh of transport fuel
- electrolyzers produce 200 TWh of hydrogen

From the inputs the following outputs can be produced by the model; energy balances, resulting annual productions, fuel consumption, import/exports and total costs including income from the exchange of electricity [24].

Utilising credible existing data is fundamental in providing a relevant and useful assessment in comparing the 2 scenarios. The NG Gone Green FES provides the bulk of the data for demand and generation capacity. For a complete description of the assumptions that have gone into the NG Gone Green FES see Ref. [12]. Data taken from the NG Gone Green FES to form the EnergyPLAN [25] model inputs include:

- total annual electricity and gas consumption (TWh) including a break-down for both heating and transport. Based on the annual consumption figure it was necessary to then create a representative hourly profile to cover the 12-month period which was fed into EnergyPLAN
- all demand and supply numbers for the model are dealt with in units of TWh to ensure a common unit is used at all times for energy balancing
- generation capacity for the chosen technologies (MW)
- storage capacity in power rating (MW) and energy rating (GWh)

Further model inputs taken from relevant sources:

- efficiencies for chosen generation are provided by the model itself which was developed by Aalborg University in Denmark
- all investment costs for all technologies including operation and maintenance and fuel costs have been sourced and are shown in the [supplementary data](#)
- the output from the generation technologies are based on the model inputs. EnergyPLAN provides the distribution data and capacity factors for the different technologies to ensure the annual value is most accurately represented in the hourly format

The outputs which will be produced from the model are listed in Fig. 4. Values for production, consumption, import/export and natural gas exchange are provided as monthly total values as this is the optimal level of detail to provide the results in an acceptable manner from a presentational perspective (see [supplementary data](#)). Fuel balances, CO₂e emissions and costs are provided as annual total figures. A market-economic simulation has been chosen for the model which identifies the least cost solution to the system in assuming an electricity market where plant operators seek to optimise their assets' profits [26].

2.1. Key assumptions for both scenarios

- energy demand is the same
- where possible all cost assumption data identified in [appendix A.1](#) was taken from sources which provided indicative predicted costs for 2050. Where this information was not available present day costs were used
- the scenarios do not make assumptions regarding the UK's future economic development and growth which are undoubtedly factors that will impact upon future technology deployment but which are outside the scope of this study
- changes in end user preferences regarding their heating technology is unlikely to occur without incentives established by the UK Government. The costs of any incentives are not included
- whilst fuel production costs are included in the model refuelling infrastructure costs, as well as vehicle costs, are not included in the overall system cost

2.2. Nuclear and renewables scenario

The base line data for the scenario was taken from NG's Gone

NG Gone Green FES annual gas & electricity demand variation
by sector (excluding losses) 2015–2050

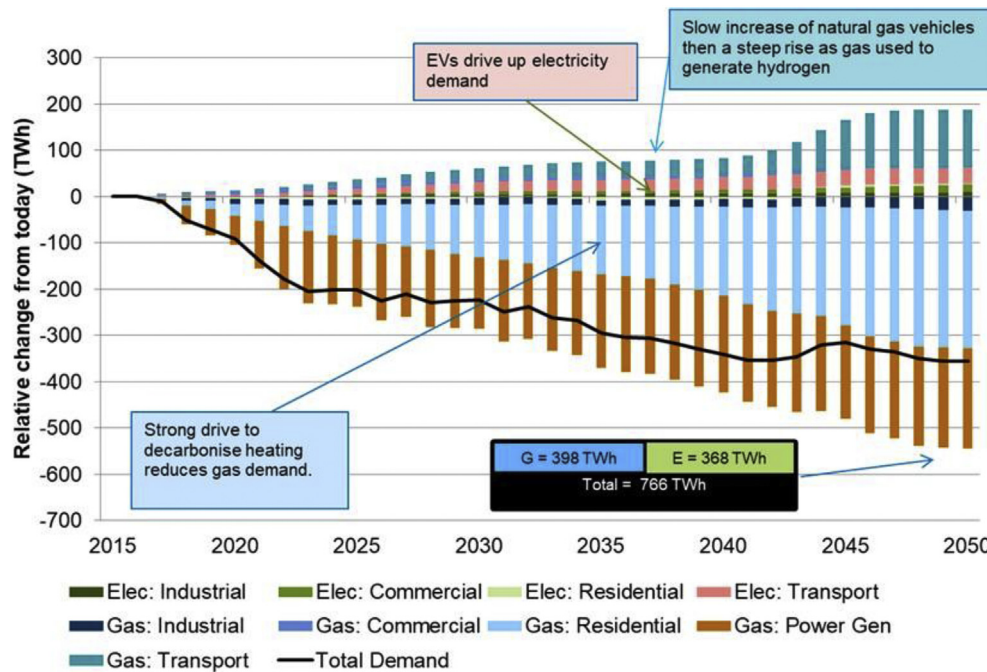


Fig. 2. NG Gone Green FES [7] annual gas & electricity demand variation by sector (excluding losses) 2015–2050.

Green FES. Table 2 shows the energy demand for the 2050 nuclear and renewables scenario.

Based on the NG Gone Green scenario [7], an annual gas demand of 392 TWh shown in Fig. 5 -24 TWh from the total comprise of losses- and electricity demand of 399 TWh was used to configure the model with a breakdown of the input categories shown in Table 2.

Capacities for generating technologies shown in Fig. 3 are also based on the Gone Green FES and include: 51 GW of wind, 38 GW of photovoltaic, 20 GW of nuclear 8.2 GW of wave and 1.1 GW of river hydro. In addition a small amount of gas CHP and biomass CHP was utilised as part of district heating networks.

In establishing the necessary storage capacity and transmission capacity to achieve a working model the capacities were configured as those provided in the Gone Green FES. The model immediately described them as being too small to enable a working energy

system whereby supply could match demand. The capacities were then gradually increased until they were large enough for the model to work. Electricity storage capacity came to 9.6 GW along with 116 GW of transmission capacity.

Some of the underlying numbers that sit behind the transport inputs to the model are shown in Table 3.

2.3. Gas with carbon capture storage (CCS) scenario

The final annual electricity demand under this scenario is practically the same as the other scenario with 390 TWh. However a difference was that the CO₂e emissions output came to 575 million tonnes far in excess of the 2050 target. To mitigate this sufficient CO₂e sequestration was added to the model, to ensure target compliance, at an assumed electricity consumption of 0.37 MWh/tonne of CO₂e [23]. The result of which increased overall electricity demand to 475 TWh.

The gas demand is unsurprisingly far higher at 1110 TWh as this number includes both hydrogen and natural gas. Generation technologies and corresponding capacities were naturally very different under this scenario. No electricity is generated from renewables and 5 GW of industrial CHP electrical capacity has been installed with boilers also being utilised. Hydrogen production - shown through the model - is from electrolyzers as the model does not allow for SMR to be represented. It should be noted that production of hydrogen from SMR is likely to be cheaper than electrolysis. To reflect the cost of hydrogen production more accurately an adjustment is made in the results section to better represent an energy system costs based on the anticipated production method of SMR.

The conversion costs of installing new boilers and cooking appliances compatible with hydrogen have not been included in the model. It has been estimated that the cost of converting the gas grid to 100% hydrogen would be around £200 billion to 2050 where

Table 2

Annual electricity & gas demand from National Grid Gone Green future energy scenario [7].

Sector	TWh
Gas demand	
Residential	128
Industrial	103
Commercial/Other	137
Transmission and Distribution Losses	24
Total Annual Demand	392
Electricity demand	
Industrial and commercial	205.2
Residential	34
Gas for hydrogen (transport) to use in HGVs	89
Natural gas vehicles	12.51
LNG for vehicles	24.69
Power station demand	33.6
Total Annual Demand	399

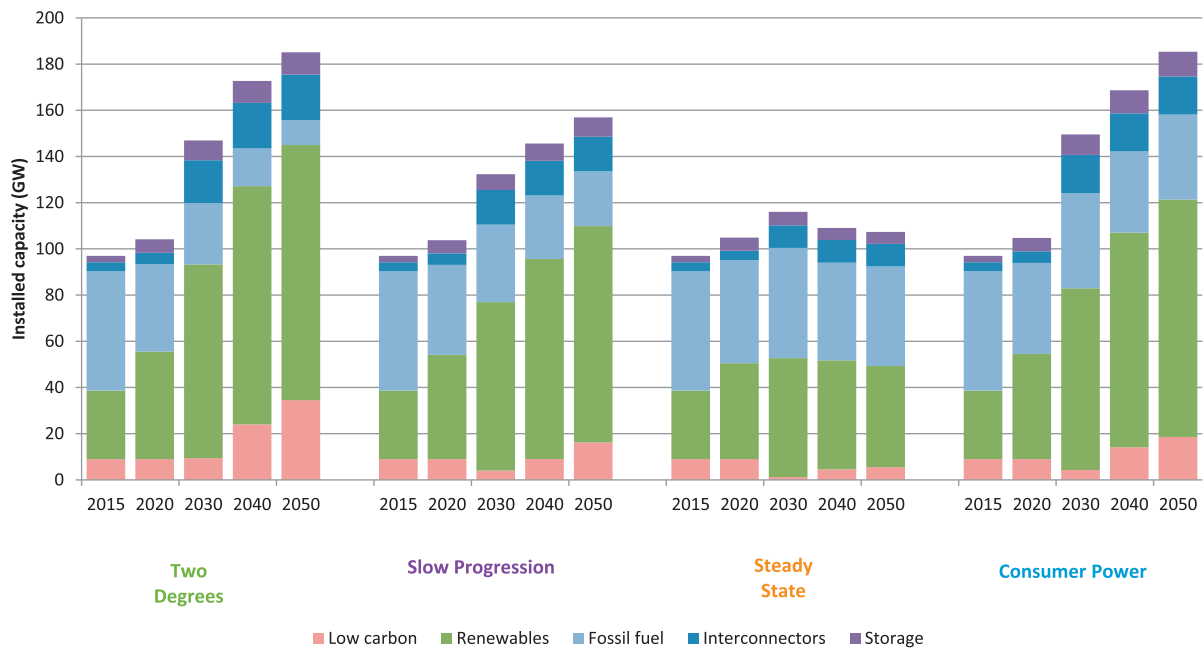
Installed Capacity by type (GW)

Fig. 3. NG FES [7] installed capacity by type for Gone Green scenario (GW).

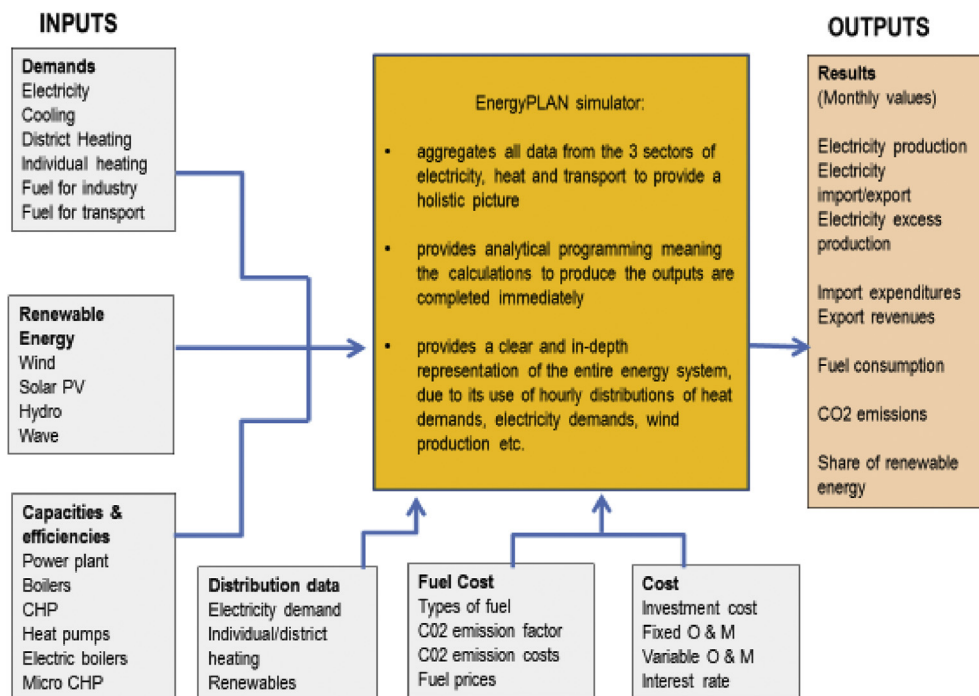


Fig. 4. Structure of EnergyPLAN advanced system energy analysis tool.

hydrogen is meeting 75% of total heat demand [4]. The KPMG study on which the scenario is based suggests that hydrogen would meet close to 50% of residential and commercial energy demand in the UK and would be in the region of £104–122 billion [9].

A larger 1000 GW of transmission line capacity had to be installed to ensure the model could function from a technical

perspective highlighting the large amount of electricity that would need to be imported under this scenario. Although it should be noted that some of that capacity would be required for the electrolyzers which under the envisaged scenario will not be utilised. From the overall amount of energy provided to fuel transport close to 50% is hydrogen gas, 26% electricity and the remainder petrol.

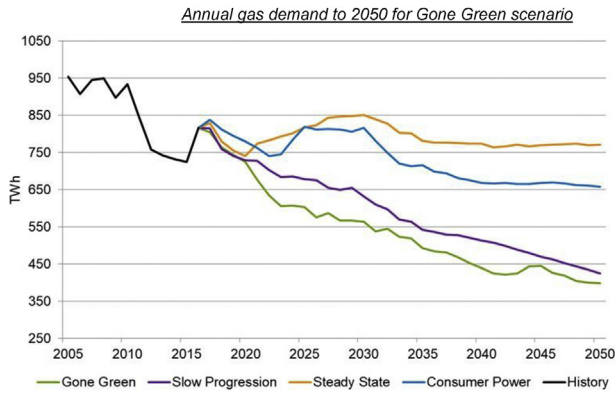


Fig. 5. NG FES [12] annual gas demand to 2050 by scenario (excluding interconnector exports).

Table 3

Vehicle numbers & transport energy demand for 2050 nuclear & renewables scenario [7].

Plug in EVs	Plug in hybrid EVs	EV total annual consumption (TWh)	Peak demand (GW)
25,133,000	1000	35	5.5
HGVs fuelled by hydrogen	HGVs fuelled by natural gas	Hydrogen gas annual consumption (TWh)	Natural gas annual consumption (TWh)
385,200	210,000	89	37

Some of the underlying numbers that sit behind the transport inputs to the model for this scenario are shown in Table 4.

3. Results

The results are presented in the following order. The headline quantitative data produced by the model are shown first with an explanation of the sensitivity analysis undertaken.

Commentary is then provided to further describe the result by each evaluation criteria. Finally, qualitative results relating to the technology viability of each scenario is then given.

3.1. Energy trilemma indicators

After inserting all input data, listed in section 2, into the model for both scenarios the following head line results were produced shown in Table 5.

A sensitivity analysis has been carried out to better understand the potential accuracy of the results from the model. A 10% increase or decrease of the demand input for the nuclear and renewables scenario brought about an averaged 8% increase or decrease for the 3 energy trilemma outputs. Similarly for the gas CCS scenario a 10% increase in demand produced a 7% averaged increase in output whilst a 10% decrease in demand resulted in an 8% averaged reduction in output. This suggests a good level of accuracy in the study results.

EnergyPLAN does not have an option for producing hydrogen from SMR and can only represent hydrogen production from

electrolysis. In order to represent the scenario as provided by NG it is necessary to reflect what the actual cost of SMR would be.

The approach to achieving this involved determining what, based on the model outputs, the cost of production for 1 TWh of hydrogen from electrolysis would be and to then remove these costs from the overall modelled cost and replace them with that of SMR.

Assuming a capital cost of £870,000/MW-e [27] for an electrolyser, a 20 year life span [28] and the operation and maintenance being 5% [29] of the investment cost the annual investment cost for the electrolyser – provided by EnergyPLAN [see supplementary data] – is £37.9 billion. Dividing the annual investment cost by the 620 TWh of hydrogen production required provides a cost of £61, 169, 355/TWh or 0.061 pence/KWh. A recent report by Northern Gas Networks [30] calculated the cost of hydrogen production from SMR to be 0.05 pence/KWh or £50, 000, 000/TWh. Multiplying the

value of £/TWh by 620 TWh provides an annual investment cost of £31.0 billion. This reduces the overall annual system cost by £6.9 billion to £381.6 billion.

3.1.1. Security

The nuclear and renewables scenario shows imports per year totalling 505.5 TWh. The break down is 11.6 TWh/yr for electricity imports with gas at 493.9 TWh/yr. The average price of these imports is given as £193/MWh.

In terms of gas security the UK's natural gas production has reduced – as a trend – over recent decades due to depletion of existing gas fields. Subsequently, more gas has been imported to meet this shortfall making the UK more dependent on external suppliers [31]. In 2015 a little under 50% of sourced gas was produced in the UK. Nearly 40% came via pipelines mainly from Russia. The remainder came from Liquefied Natural Gas (LNG) imports from countries such as Qatar [15].

For gas CCS the model shows that an amount of energy four times greater than in the nuclear and renewables scenario is required to be imported at 2220 TWh/yr. The average price for importing is £198/MWh.

3.1.2. Affordability

Heavy investment is required to construct a nuclear power station but low operation & maintenance (o&m) costs mean generation is cost effective [32]. In running 20 GW of nuclear plant the model estimates that annual costs of uranium will be around £24.8 billion.

Table 4

Gas CCS scenario transport energy sources [9].

Energy mix in 2050 - Transport (Road & Rail)	
Source	TWh
Hydrogen	200
Electricity	107
Petrol	100
Total	407

Table 5

Study results taken from research model.

Criteria	Metric	Unit	Scenario	
			Nuclear & renewables	Gas with CCS
Security:	Total amount of energy imported	TWh/yr	505.5	2220.0
Affordability:	Overall annual energy system cost provided from EnergyPLAN model	£bn	47.4	388.5
	Post-hoc overall annual energy system cost to reflect hydrogen production from SMR	£bn	N/A	381.6
Sustainability:	C02e emissions provided from EnergyPLAN model	MtCO2e	51.0	164.8

Total annual costs of running this system are estimated at £47.4 billion which is approximately 8 times less than the gas CCS scenario.

The overall annual costs for the gas CCS scenario are £381.6 billion. By far and away the largest investment cost is that of pumped storage (appendix C.2). The difference in investment for interconnection is significant with £3446 million for nuclear and renewables whereas for gas CCS it's far larger at £29,553 million. CCS systems are presently very expensive. Three main approaches are currently considered for CCS which are pre-combustion, post-combustion and oxyfuel combustion. It has been claimed that, for example, through post-combustion CCS the cost of electricity could increase by more than 30% for a gas-fired plant [33].

3.1.3. Sustainability

For the nuclear and renewables scenario the model estimates that there would be an overall net count of 51 million tonnes of CO₂e emissions which is within meeting the 2050 target. However there is no negating the fact of the potential long term negative impact of the radioactive waste from nuclear if not adequately treated – this is covered further in technology viability.

Fig. 6 is based on output information from the model. Whilst the graph is not fully representing how a MAC Curve would be expected to look – as it is not showing actual costs of abatement from 2015 through to 2050 – it does however provide some illustration of comparing the impact of each technology by cost and CO₂e abatement.

For gas CCS the model has allowed for 575 million tonnes of CO₂e removal by CCS technology. This brings the total emissions to 164 million tonnes which meets the target given in Table 1. The CO₂ removed from the natural gas during SMR and accounted for within

the 575 million tonnes removed would still however need to be suitably stored. Once CO₂ has been removed it must be delivered to a place of storage or used for an industrial purpose. For this a safe and economically viable system of transport will be an important component of any CCS project [33]. Transport could involve tankers, ships or pipelines. Due to the scenario utilising a much smaller mix of different abatement technologies and with it being less favourable a MAC curve has not been produced.

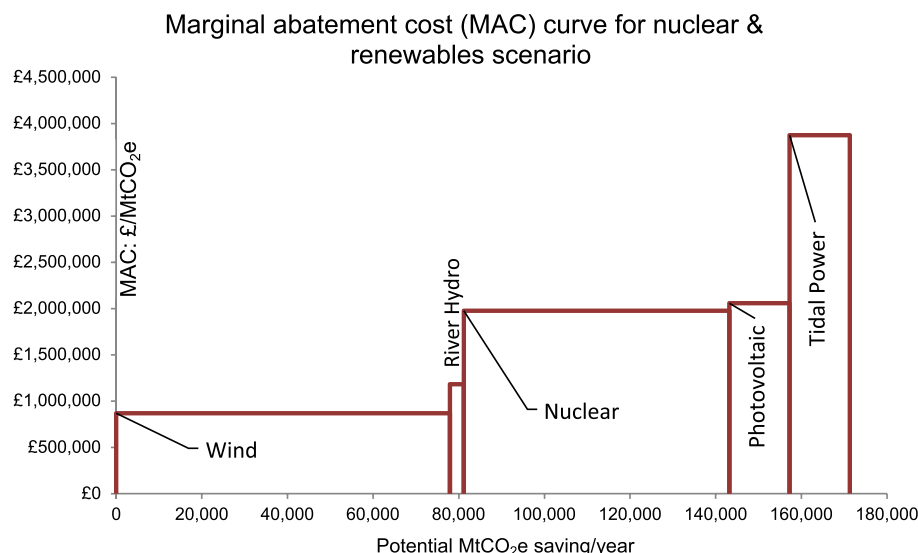
3.2. Technology viability

The results regarding the viability of the unproven technologies belonging to the two scenarios are provided in this section.

3.2.1. Nuclear & renewables viability

Whilst proposals have been put forward for storing nuclear waste deep underground in geological formations this approach has yet to be proven as a viable solution [21]. Nuclear power stations exist in around 30 countries but only around 4 of those countries have begun building storage mediums for the associated radioactive waste. Such facilities are purpose-built caves far below ground. After the waste has been treated it is placed in sealed containers, stored and expected to remain for many thousands of years [34]. However challenges exist in predicting the behaviour of such underground stores over hundreds of thousands of years.

In January 2018 the UK government began again its efforts to secure a site with the right geology and which has a local supportive community agreeing to host the site [35]. A previous attempt failed in 2013 when Cumbria County Council rejected acting as a storage location [34] highlighting the challenge that exists in establishing radioactive waste storage facilities.

**Fig. 6.** Marginal Abatement Cost Curve for nuclear & renewables scenario.

Undoubtedly, nuclear provides a solution to providing the required quantum of electricity whilst ensuring the UK meets its emission limits. Interestingly, nuclear features in all 4 of NG's 2017 FES demonstrating a belief that nuclear will form a key part of the UK's energy future. In terms of existing nuclear capacity this would need to be doubled to provide the sufficient amount of power described in the scenario. With the UK's experience in using nuclear power the technology is very much viable and it is more a question of political will, public acceptance and one of where the investment would come from to bring about more power stations in the UK.

Wind is already the UK's largest generator of renewable electricity with 18.5% of electricity in 2017 coming from wind. Onshore and offshore wind both increased by about 27% over the previous year [36]. Whilst the technology is viable it is other issues which might inhibit its deployment. Due to constraints on wind resource generators are often located in remote places where conditions are more optimal for wind farms. Such locations incur - in general - higher transmission charges due to the further distance the generator is positioned from the end user. For example in the Western Isles of Scotland maintaining transmission infrastructure is in excess of five times more than the cost for a generator in Northern Scotland [37]. Higher charges which are based on the generator being in a more remote location will unfortunately make such renewable projects less attractive [38].

The Carbon Trust in its 2008 study [39] stated the UK could deliver at least 29 GW of offshore wind power by 2020. However for this to happen greater investment is needed, suitable sites made easier to access, whilst also consideration for modifying the charging system to address the charges disparity.

3.2.2. Gas CCS viability

The premise behind CCS is that captured CO₂ is transported and injected to at least a km below surface levels for storage in geological reservoirs such as depleted oil and gas fields or saline aquifers [33]. The assumption underpinning this is that these structures have contained oil and gas for many thousands of years which can be used as proof of principle that they could store CO₂ [40].

Doubts exist over UK CCS capability as the government has withdrawn funding in developing CCS. Its potential, in delivering a future carbon compliant energy system, is clear. The Committee on Climate Change (CCC) and Energy Technology Institute (ETI) have both stated that without CCS the costs of transitioning to a low carbon system might increase two-fold [31]. In the UK CCS has not been proven at a commercial scale. Globally, a 2012 study [33] has identified around 70 CCS projects, of which the vast majority were at early planning stages with less than 20 of them in operation or even under construction.

Regarding the feasibility of a hydrogen gas network there exists an ongoing UK irons mains replacement programme due to be completed in the early 2030s. The programme is substituting old pipes with plastic pipes which are able to carry hydrogen. This requires a coordinated planned switchover for different parts of the grid. This conversion would also include a full replacement of gas appliances (e.g. boilers and cookers) with hydrogen compatible ones [20].

The H21 Leeds City Gate Study [30] has shown that the existing gas network for Leeds has sufficient capacity for conversion to hydrogen and that such an undertaking is possible.

However the study also concluded that uncertainties remain over public acceptance, identifying where in the UK it makes sense to convert as suitably located geological formation for hydrogen storage and CO₂ storage is required. Further work to understand the feasibility of such an undertaking is certainly required in the first

instance [20]. According to Policy Connect [4] to achieve the hydrogen conversion at sufficient scale by 2050 a decision from the government would be required by the early 2020s. Ahead of this decision a suitable amount of Leeds-type trials should have been undertaken and proven to be successful.

4. Discussion

The purpose of this study is to determine which scenario might be more preferable in terms of the UK meeting its 2050 GHG emissions reduction target. The criteria to determine this includes energy security, affordability, sustainability and technology feasibility. In concluding this analysis a better understanding of whether there is a future for gas can be gained.

In assessing future energy systems there is inherent uncertainty in predicting advances in technology and supplies of differing fuels a long way into the future [31]. Whilst the model made use of many cost assumptions - listed previously - it is important to make a distinction between assumptions and research limitations. This can highlight how the analysis could be improved in an ideal world with better information resources. The study evaluation criteria are addressed in following order:

4.1. Energy Security – what is the level of reliance on importing energy from other parts of the world?

In guaranteeing a secure supply of electricity nuclear power arguably is the only scalable baseload technology envisaged in the 2050 scenarios. In its favour, compared to some of the other energy sources, it can avoid the volatility of changing fossil fuel prices as well as maintain low carbon credentials [21]. The gas CCS scenario contains a far greater quantity of gas imports highlighting the UK's dependency on other countries to meet its current but also future potential gas demand. It should be noted however, that the UK does import all of its uranium from abroad, with Kazakhstan an example of one such exporter.

An increase in electricity generation from wind would involve a variety of challenges. Denmark, for example, has a high proportion of electricity generated by wind, a high level of interconnection with neighbouring countries (8.16 GW) with good integration of heat and electricity sectors. Denmark has a peak demand of around 6.0 GW [41]. In contrast the UK's system has much less integration between electricity and heat and a much smaller interconnector capacity of 3.5 GW [42] relative to peak demand of around 52 GW [43].

On this point, with significance to the two scenarios considered, a study undertaken by Heuberger et al. [22] has argued that an energy system based on combined cycle gas turbine with CCS can displace offshore wind and interconnection capacity. The effect of this, interestingly, would be to reduce UK dependency on foreign sources of energy from an interconnector point of view.

4.2. Affordability – what is the full cost of providing energy under the given conditions?

In order to produce the MAC curve graph, from the model, output data was obtained on the amount of electricity produced from a given technology. The CO₂e emissions for utilising the same quantity from grid electricity with 2014/15 emissions factor [44] was then calculated to determine what the cost per tonne of CO₂e saved would be. Whilst there is a recognised limitation in the exactness of these numbers the graph can at least illustrate the comparative cost of the technologies and their CO₂e reducing impact against each other.

Required interconnection is far larger for the gas CCS scenario

resulting in a much larger investment cost of a magnitude of 8. This represents the larger amount of electricity to be imported under this scenario.

4.3. Sustainability – what is the environmental impact of establishing an energy system based on the given scenarios?

Both scenarios from the perspective of the model are compliant from a 2050 GHG emissions target standpoint. Equally both approaches contain large question marks over their sustainability credentials. In considering how sustainable nuclear electricity is it cannot be overlooked that a by-product of this process is huge quantities of radioactive waste. The treatment of this waste is addressed in technology feasibility. It is clear however that from a generation point of view nuclear can provide a large contribution to providing the required quantum of electricity whilst ensuring the UK meets its emission limits.

A perhaps broader point to make is that the current framework for emissions accounting could benefit from further development. At present emissions accounting does not include those upstream emissions from the gas which the UK imports which are therefore not actually represented in the carbon intensity of the UK electricity grid [31]. As a result these emissions are not included within the model.

4.4. Feasibility of technology in 2018 - how mature - as well as technically and financially viable - are the proposed technologies for both scenarios?

Both scenarios contain large question marks when it comes to the proven technical viability of storing radioactive waste and captured CO₂. With regards to crucial decisions that need to be made for the nuclear scenario certainly investment and identifying an appropriate location for the storage of this waste are required in the context of the UKERC's conclusion that the average time for an energy generation technology to become commercialised is 48 years [11]. With only 32 years to 2050 only 2/3 of the technology readiness period remains and if the UK is to effectively double its existing nuclear plant capacity this issue requires an immediate resolution.

The viability of converting the gas grid to hydrogen has been covered in the results section. Whilst the different stages of CCS are already operational it is the linking of them all together where there is not the experience. An integrated CCS system is very much in an innovation stage with high costs and uncertain learning rates [33]. Beyond the need to prove the aforementioned technical aspects of CCS there likely exists a need to ensure drivers remain to encourage CCS activity. CO₂ separation has been undertaken for a long time in the oil and gas industry however capture from power plants is minimal. In 2012 only 5 projects were noted as taking place which were testing CCS as an integrated system with each project injecting 0.7–1.5 Mt CO₂ per year [33]. It has been estimated that approximately 100 CCS projects need to be implemented by 2020 and over 3000 by 2050 in order to reach the goal of restoring global temperatures by 2° [33]. Suggestions of where intervention is required to scale up CCS activities include financial, regulatory and legal. The continuation of imposing a fine on CO₂ emissions or else mandating CO₂ mitigation are options. Tax breaks or else government subsidy could also support greater CCS undertakings [40]. A study by the Committee on Climate Change in 2018 [45] concluded that not including CCS in the 2050 scenario would make meeting the target very challenging. In addition without CCS the cost of meeting the 2050 target is likely to be significantly higher.

There are estimates that the North Sea could store just under 80,000 MtCO₂ which could be sufficient for the UK - in a high

hydrogen scenario - where up to 150MtCO₂ per year of CO₂ are produced by 2050.

5. Conclusions

Whilst recognising the previously described limitations of this study it can be reasonably concluded that based on the study evaluation criteria outputs a 2050 energy future based on nuclear and renewables is the most preferable scenario from the 2 options considered.

Gas, most certainly, for the immediately foreseeable future will play a key role in the UK energy mix. However its future needs to be decided upon in the medium term. If it will continue to play a big role in providing the UK's energy it must rely on the successful development, roll out and scale up of CCS. Whilst this study has shown the overall cost of a gas CCS scenario to be far higher than nuclear with renewables it has however shown that such a scenario is technically possible – including the conversion of the gas grid to carrying hydrogen. This scenario could therefore be pursued by the UK government if it preferred. With SMR understood to be the cheaper option for the production of hydrogen this means that natural gas would remain the UK's key energy resource.

Regardless were the UK to pursue a nuclear and renewables scenario gas would still be utilised – just not in such a prevalent role. If nuclear power is not pursued through to 2050 then certainly a mix of both renewables and fossil fuels will be required to meet the 2050 target [13]. The knock on effect of utilising the fossil fuel element would again require CCS to be operational at scale.

5.1. Further work

In suggesting further work that could be undertaken to develop the existing study an immediate action could be to refine the accuracy of the costs represented by the model. It could be worth refreshing all the cost model assumptions as updated literature is made available. In addition, a further assessment of the overall required capacities for both interconnector and transmission should be undertaken - particularly in light of electrolysis not being required - in order to provide a more accurate overall system cost prediction.

I believe this study has been carried out in a very robust and informed manner meaning it adds value and can go some way to providing a holistic assessment of a future UK energy system. It certainly contributes to existing academic debate on how the UK can achieve a 2050 compliant energy system.

However in suggesting a project to further develop this initial study points of further investigation could include the costs of transport vehicles, refuelling infrastructure as well as appliances such as domestic boilers and cookers. A study which was to include these costs for both scenarios and make a comparison of them to a baseline of no action taken between now and 2050 could provide a more clearer picture of what the cost of the UK becoming 2050 GHG emission compliant might be.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.renene.2019.04.052>.

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